PARTICLES WITH CHARM AND BEAUTY

J. Rosner, Talk at Chris Quigg Symposium, Fermilab, December 15, 2009

Enjoyable collaborations with Chris started in early days of charm

Some issues that concerned us then and where they stand today

- Baryons with heavy (c, b) quarks (early paper with B. Lee on Λ_c, Σ_c, Σ_c^*)
- Fleshing out the quarkonium spectrum: h_c, η_b, B_c
- Coupled-channel effects and new quarkonium states
- Multi-particle final states in heavy meson decays
- Radiative charmonium transitions and charmed quark magnetic moment

Our earliest joint paper dealt with hyperon beams: Phys. Rev. D **14**, 160 (1976).

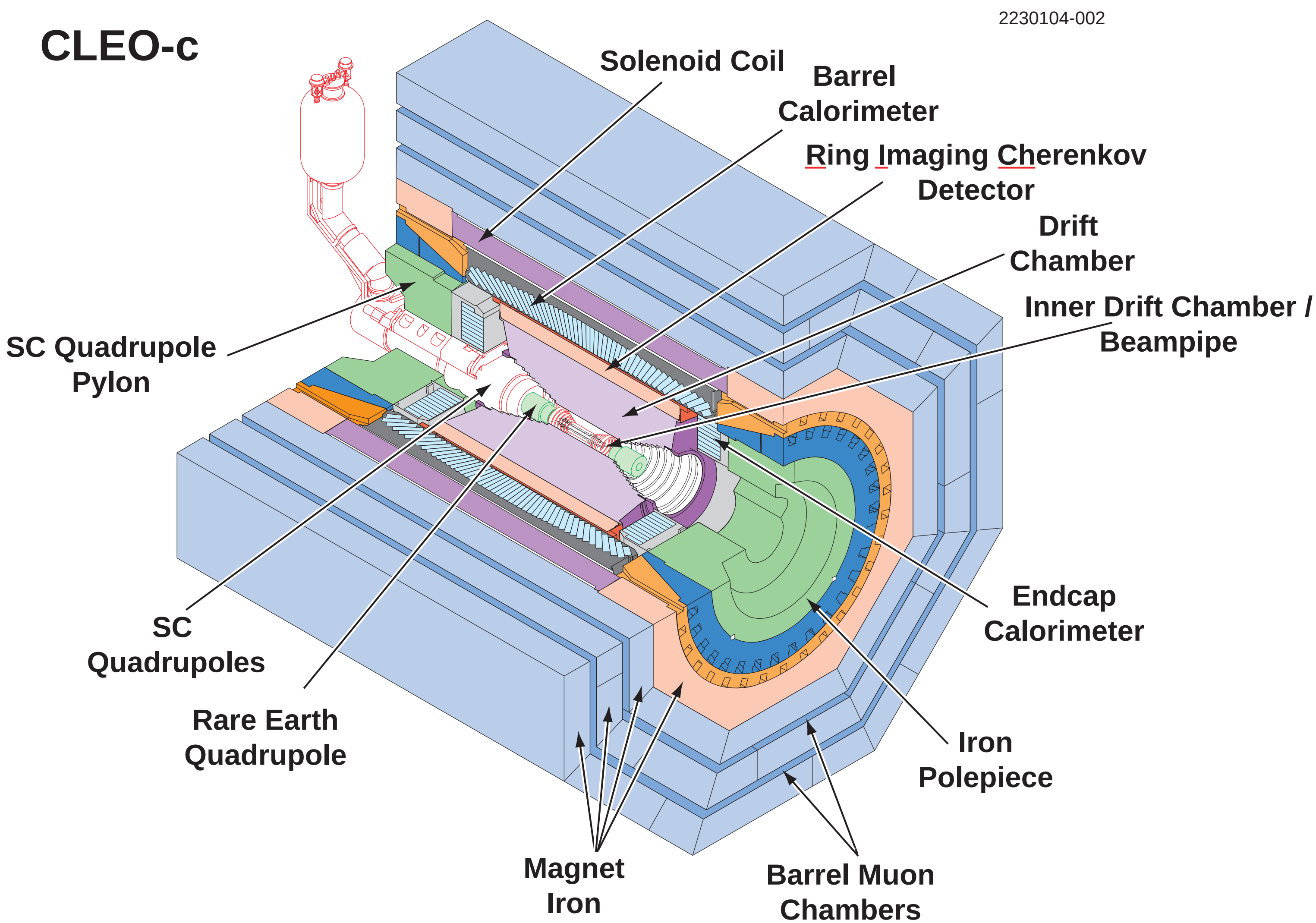
We were concerned with hadron physics; Σ–π scattering still timely

SELEX: doubly-charmed baryon candidates (Engelfried, HQL 2006, hep-ex/0702001)

Not confirmed by BaBar [PR D **74**, 011103 (2006); consult for mass preds.]

THE CLEO-c DETECTOR

Many of today's results will be as a member of CLEO; thanks to colleagues

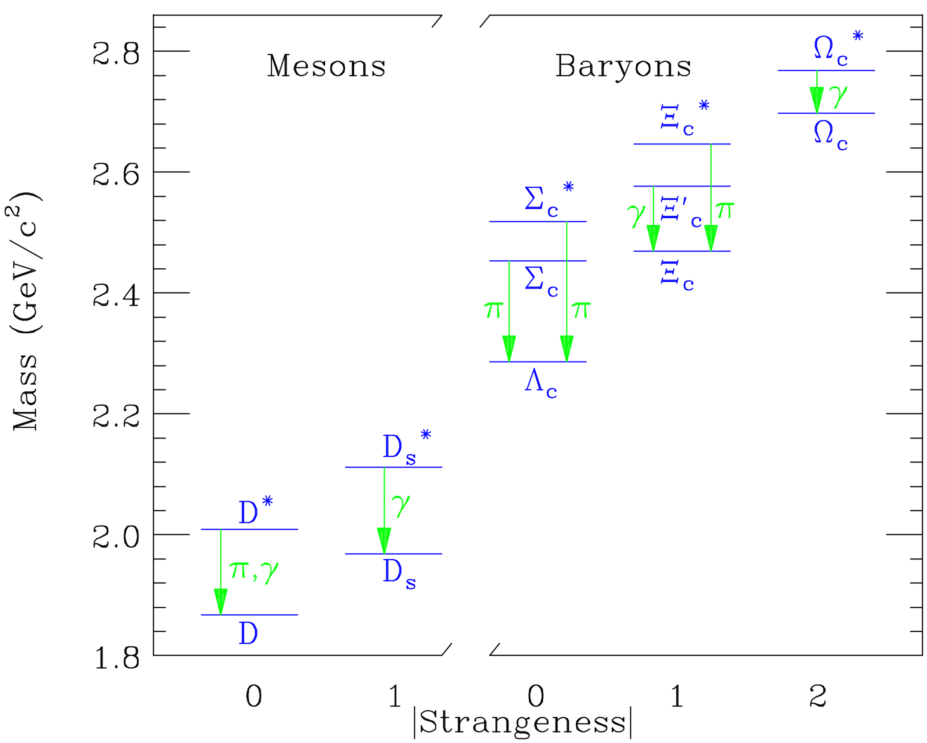


Specific features: Excellent photon energy resolution and particle identification

CHARMED AND BEAUTY BARYONS

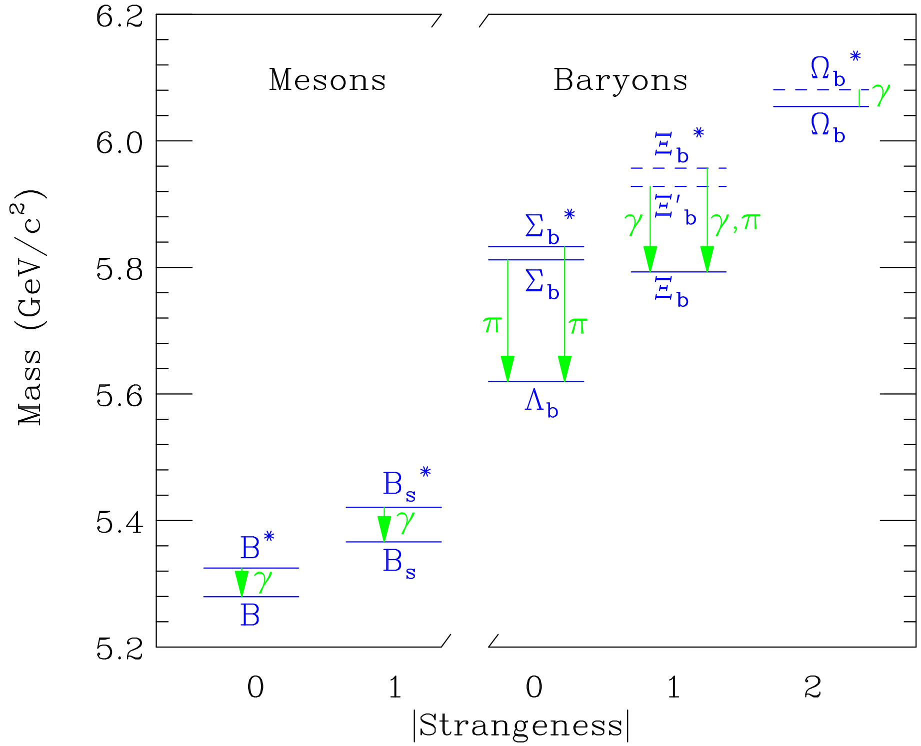
S-waves only; also orbital excitations for charmed mesons and baryons; B mesons

Hadrons with one c quark:



Latest addition: Ω_c^* seen by BaBar [PRL **97**, 232001 (2006)], consistent with quark model predictions incorporating quark mass differences and hyperfine interactions

Hadrons with one b quark:



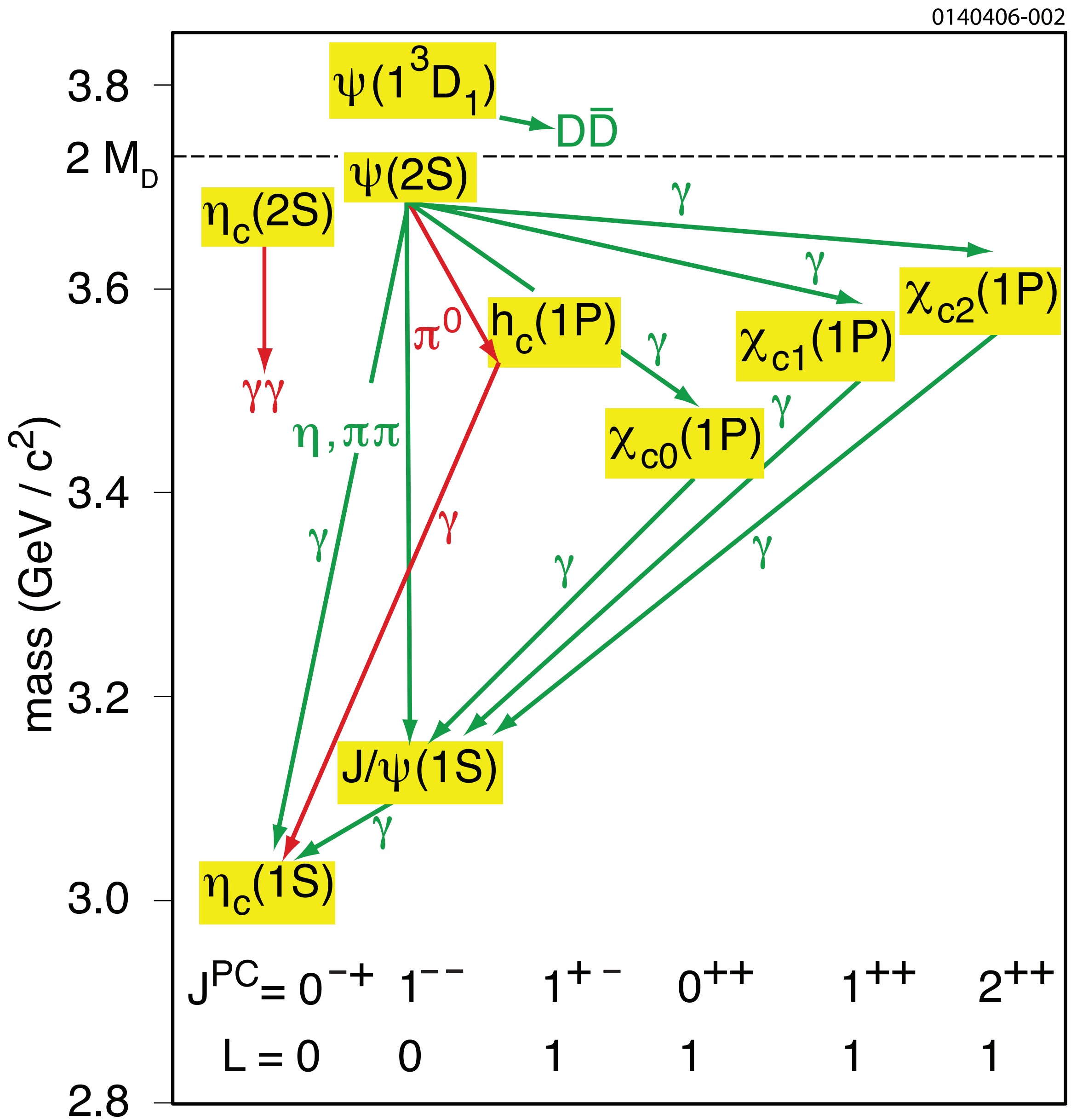
Ξ_b and Ω_b added recently

Masses agree with simple quark models [Karliner *et al.*, Ann. Phys. **324**, 2 (2009)]

$M(\Omega_b)$: CDF [PR D **80**, 072003 (2009)]

D0 [PRL **101**, 232002]: 111 MeV higher

CHARMONIUM SPECTRUM



Last charmonium state below flavor threshold discovered in 2004: $h_c(1P)$, spin-singlet

Seen in isospin-violating decay $\psi(2S) \to \pi^0 h_c(1P)$ $(\mathcal{B}_1)$, $h_c(1P) \to \gamma\eta_c(1S)$ $(\mathcal{B}_2)$

CLEO-c sample of 24.5M $\psi(2S)$ $\Rightarrow \langle M(^3P_J)\rangle - M(1^1P_1)$ $= 0.02 \pm 0.19 \pm 0.13$ MeV

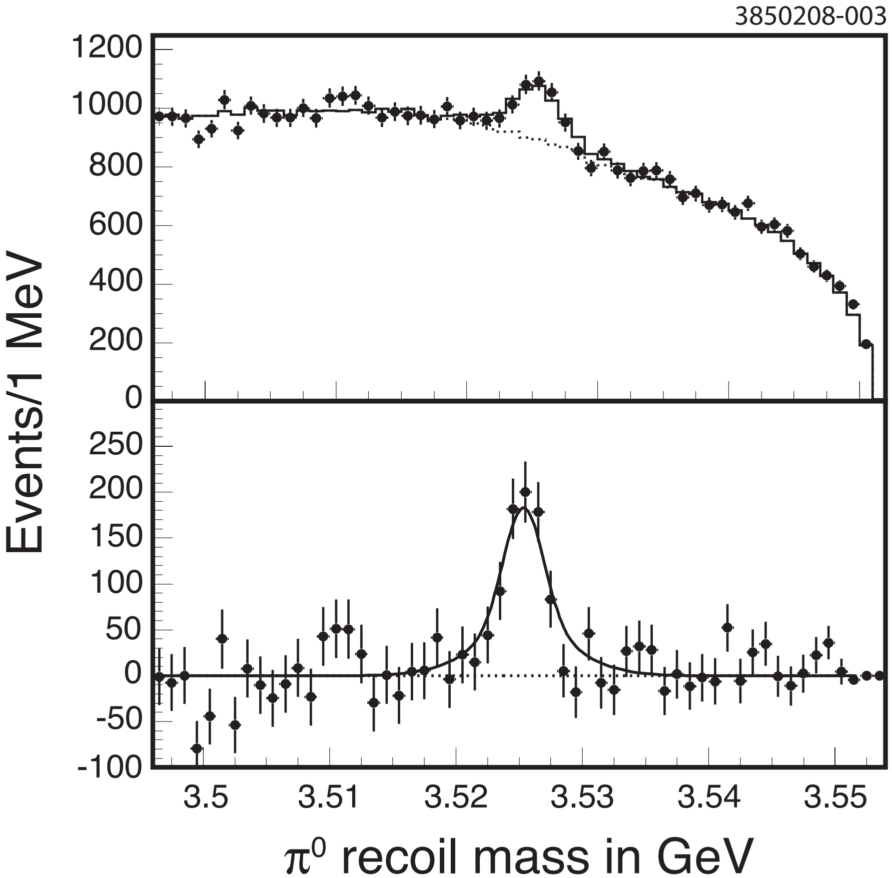
Hyperfine splitting found small between P-wave states; wave function zero at origin

Saw $\eta_c(1S)$ both inclusively and in 15 exclusive modes

S. Dobbs *et al.* (CLEO Collaboration), PRL **101**, 182003 (2008)

$h_c(1P)$ MASS SPECTRA

Inclusive $\eta_c(1S)$ decays

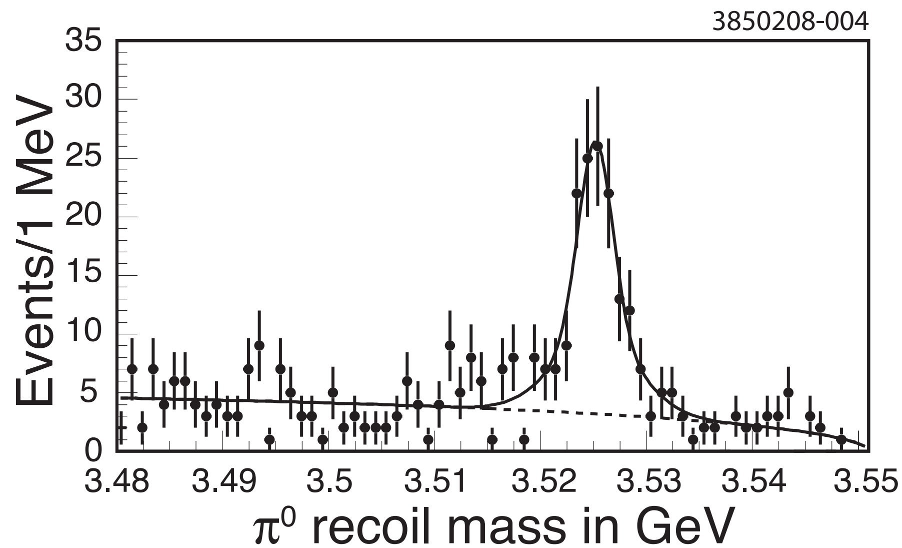


Exclusive $\eta_c(1S)$ decays

15 exclusive modes with multiplicities from 2 to 6

Inclusive: 1146 ± 118 events;

Exclusive: 136 ± 14 events

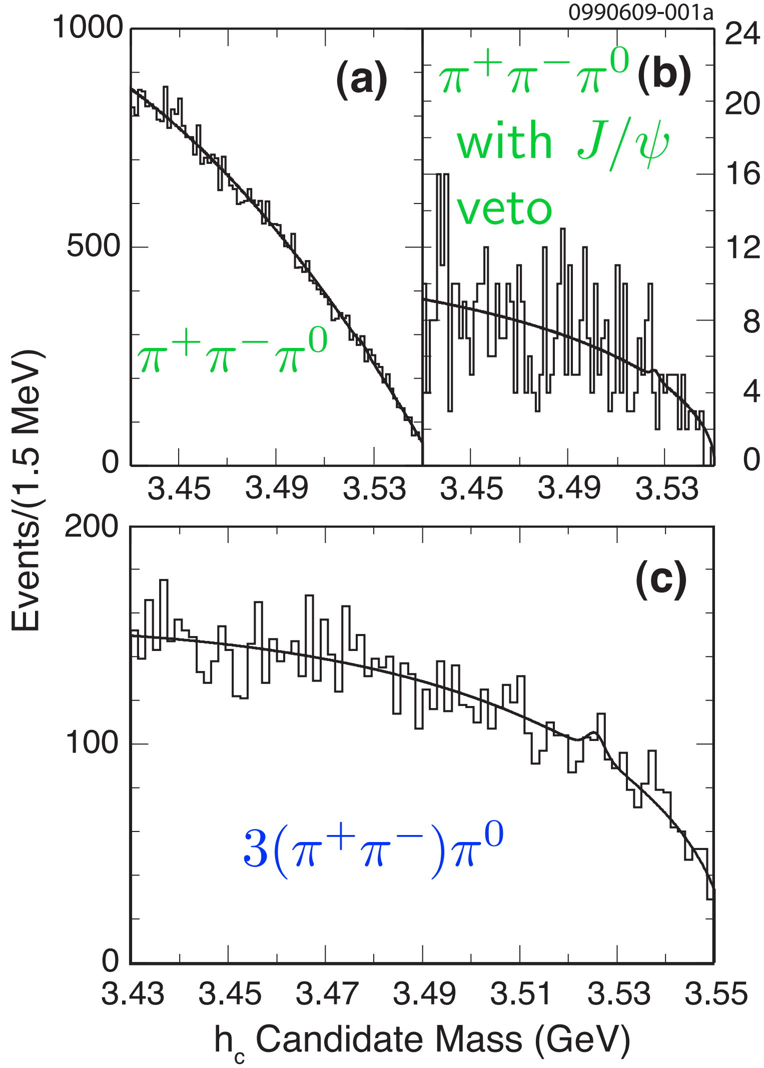


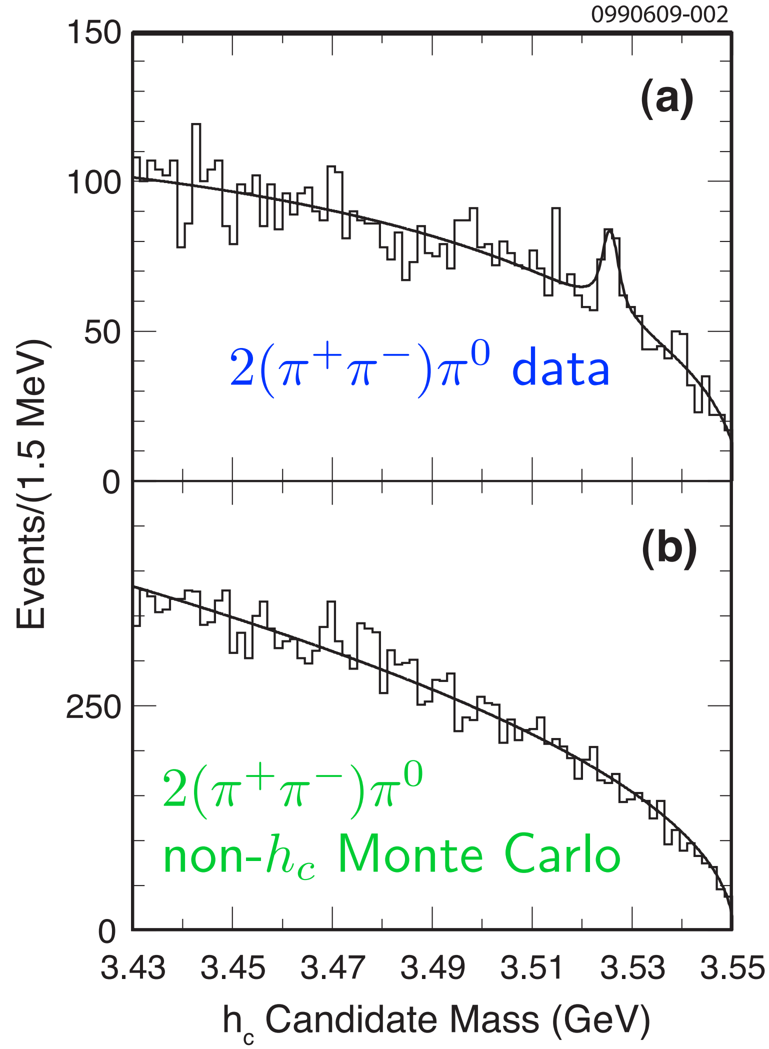
Inclusive: $M(h_c)$=3525.35±0.23±0.15 MeV, $\mathcal{B}_1\mathcal{B}_2$=(4.22±0.44±0.22) $\times 10^{-4}$

Exclusive: $M(h_c)$=3525.21±0.27±0.14 MeV, $\mathcal{B}_1\mathcal{B}_2$=(4.15±0.48±0.77) $\times 10^{-4}$

EXCLUSIVE h_c DECAYS

G. S. Adams *et al.* (CLEO Collaboration), Phys. Rev. D **80**, 051106(R) (2009)



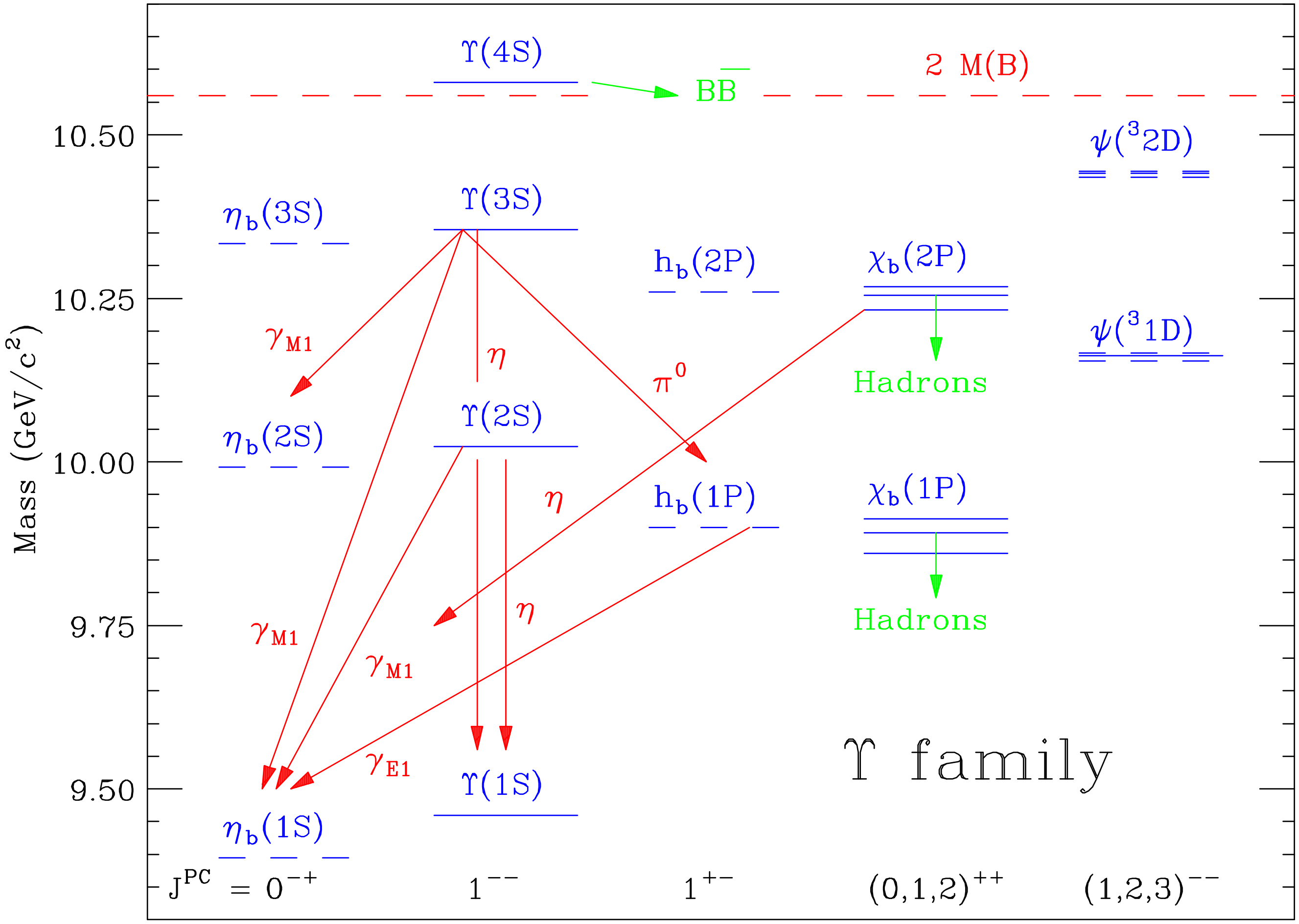


$$\mathcal{B}[\psi(2S) \to \pi^0 h_c]\mathcal{B}[h_c \to 2(\pi^+\pi^-)\pi^0] = (1.88^{+0.48+0.47}_{-0.45-0.30}) \times 10^{-5}$$

$2(\pi^+\pi^-)\pi^0$ estimated to be a few % of all hadronic h_c decays

OBSERVATION OF $\eta_b(1S)$

G. Bonvicini *et al.* (CLEO Collaboration), arXiv:0909.5474, $\Rightarrow$ Phys. Rev. Letters



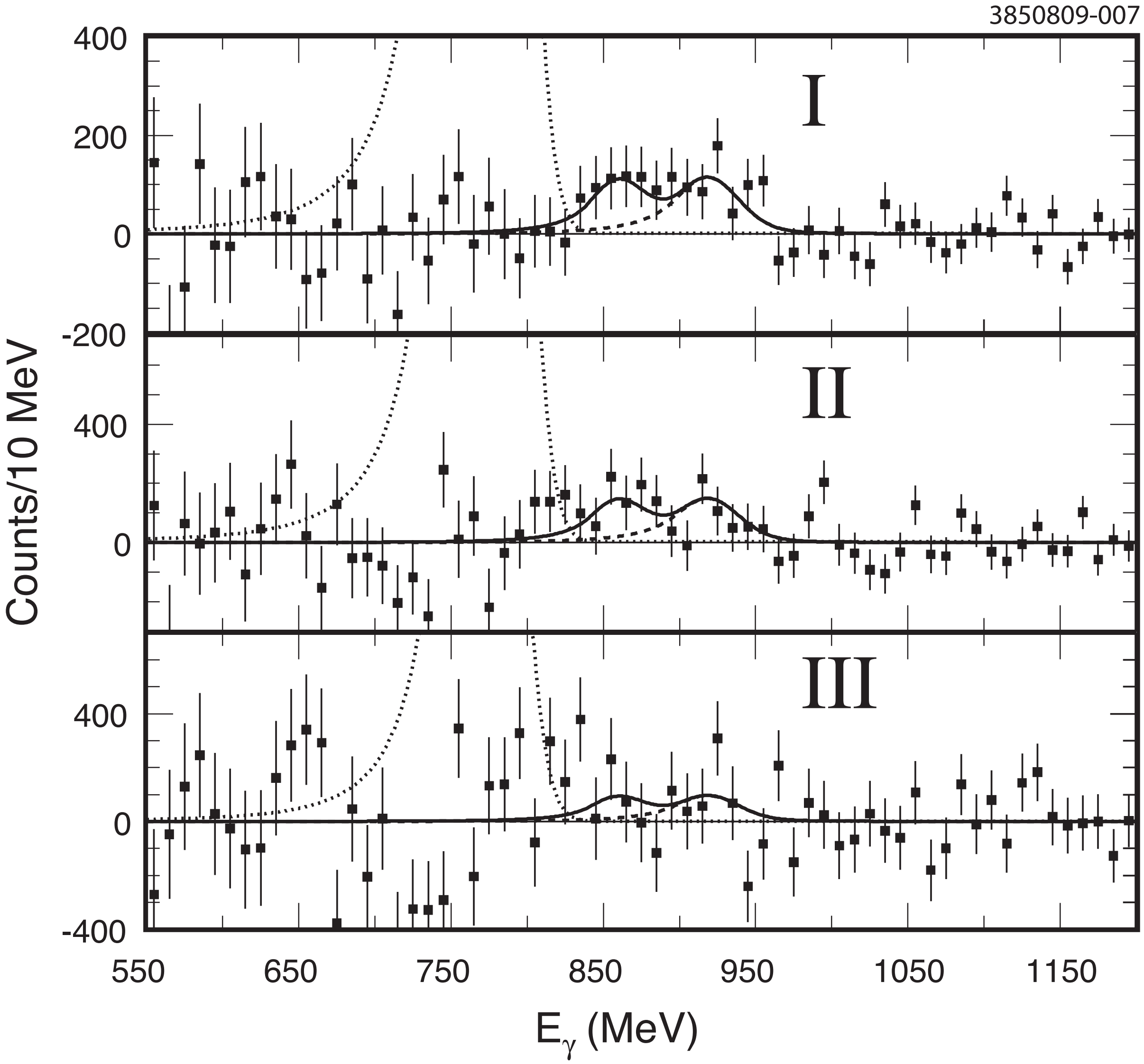
BaBar observed $\Upsilon(3S) \to \gamma\eta_b(1S)$ [B. Aubert +, PRL **101**, 071801 (2008)]

$\mathcal{B}$ slightly above earlier CLEO limit [M. Artuso +, PRL **94**, 032001 (2005)].

Prompted a re-analysis of CLEO's 5.88M $\Upsilon(3S)$ sample (vs. BaBar's 109M)

CLEO $\eta_b(1S)$ ANALYSIS

New (cf. BaBar): (1) initial-state radiation (ISR) in $e^+e^- \to \gamma(859\ \mathrm{MeV})\Upsilon(1S)$; (2) finite $\Gamma(\eta_b)$ (nominal 10 MeV); (3) angle between $\gamma(920\ \mathrm{MeV})$ and thrust axis [BaBar: $\cos\theta_T < 0.7$; CLEO: I(0.0-0.3), II(0.3-0.7), III(0.7-1.0)]



Large peak around 770 MeV due to $\chi_b(2P) \to \gamma\Upsilon(1S)$ has been subtracted

Background expected to be greatest in Bin III; fit to each $\cos\theta_T$ bin separately

$M(\eta_b) = (9391.8 \pm 6.6 \pm 2.0)$ MeV; $M[\Upsilon(1S)] - M[\eta_b(1S)] = (68.5 \pm 6.6 \pm 2.0)$ MeV

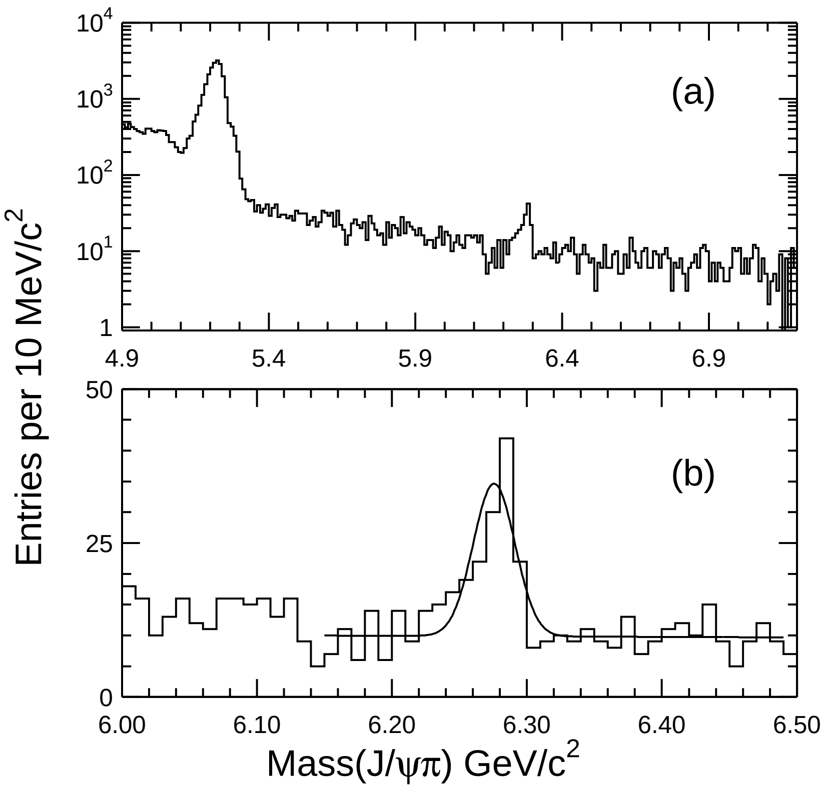
BaBar: $71.4^{+3.1}_{-2.3} \pm 2.7$ MeV; Lattice: (61 ± 14) MeV

$\mathcal{B}[\Upsilon(3S) \to \gamma\eta_b(1S)] = (7.1 \pm 1.8 \pm 1.1) \times 10^{-4}$

THE B_c MESON

Flavor-independence of quarkonium potential (see review by C. Quigg in 1979 Lepton-Photon Symposium, Fermilab) allows estimates of masses of $b\bar{c}$ states, e.g.:

Authors	Reference	$M(B_c)$	$M(B_c^*)$
E. Eichten, C. Quigg	PR D **49**, 5845 (1994)	6264 MeV	6337 MeV
D. Ebert *et al.*	PR D **67**, 014027 (2003)	6270 MeV	6332 MeV
S. Godfrey	Private comm.	6271 MeV	6338 MeV
Lattice	PRL **94**, 172001 (2005)	$M(B_c) = 6304 \pm 12^{+18}_{-0}$ MeV	
Lattice	arXiv:0909:4462	$\Delta M_{\rm hf} = (53 \pm 7)$ MeV	



Larger peak at left: $B \to J/\psi K^\pm$

CDF measured $M(B_c)$ in $J/\psi\pi^\pm$ mode: $6275.6 \pm 2.9 \pm 2.5$ MeV

Eichten-Quigg and Ebert *et al.* quote other predictions

Lattice hyperfine prediction smaller than many others but error needs reduction

Challenge to experiment: γ in $B_c^* \to \gamma B_c$

COUPLED CHANNEL EFFECTS

Eichten–Lane–Quigg, PR D **69**, 094019 (2004); D **73**, 014014 (2006): Coupled-channel effects on charmonium masses and transitions

Example: naive hyperfine estimate of $M[\psi(2S)] - M[\eta_c(2S)]$ nearly 70 MeV; reduced by more than 20 MeV by coupling to open charm

$X(3872)$ near $D^0\bar{D}^{*0} + \mathrm{c.c.}$ threshold; bound state or not?

PDG 2009 (mostly CLEO): $M(D^0) + M(D^{*0}) = (3872.81 \pm 0.35)$ MeV, to compare with BaBar measurements $M[X(3872)] = (3871.4 \pm 0.6 \pm 0.1)$ MeV in $J/\psi\pi^+\pi^-$ mode ($\surd$ CDF) and $(3875.1^{+0.7}_{-0.5} \pm 0.5)$ MeV ($D^0\bar{D}^{*0} + \mathrm{c.c.}$ mode).

Spectrum depends on final state; cf. $\Lambda(1405) \to \Sigma\pi$ and effect on K^-p spectrum

If $X(3872)$ is associated with S-wave $D^0\bar{D}^{*0} + \mathrm{c.c.}$ threshold, its $J^{PC} = 1^{++}$; favored by Belle but CDF still permits 2^{-+}

If $J^{PC}[X(3872)] = 1^{++}$ and it is not $2^3P_1(c\bar{c})$, it can mix with such a state (e.g., one above 3.9 GeV decaying to $\omega J/\psi$); this would permit $X(3872) \to \gamma J/\psi$

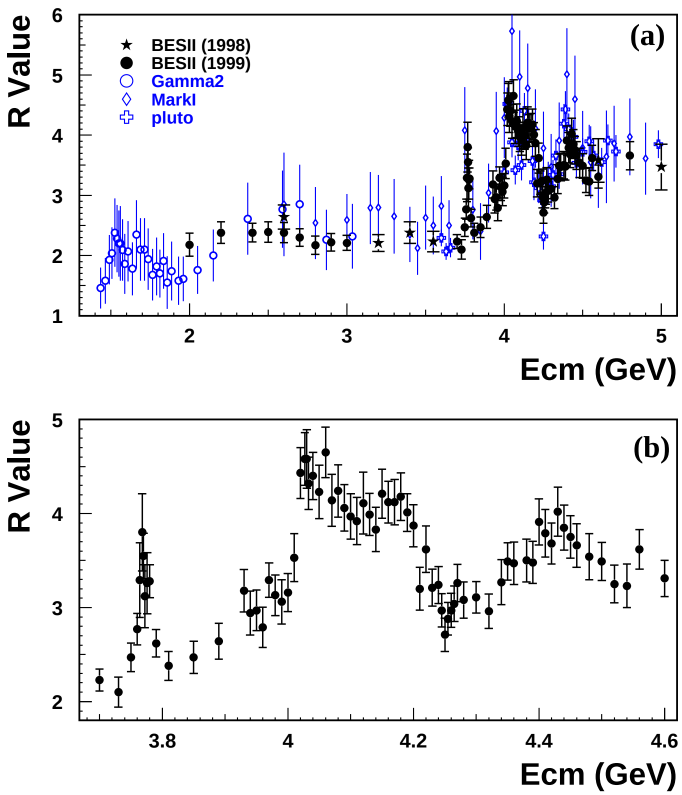
Interplay of closed and open S-wave channels reminiscent of *Feshbach resonances*

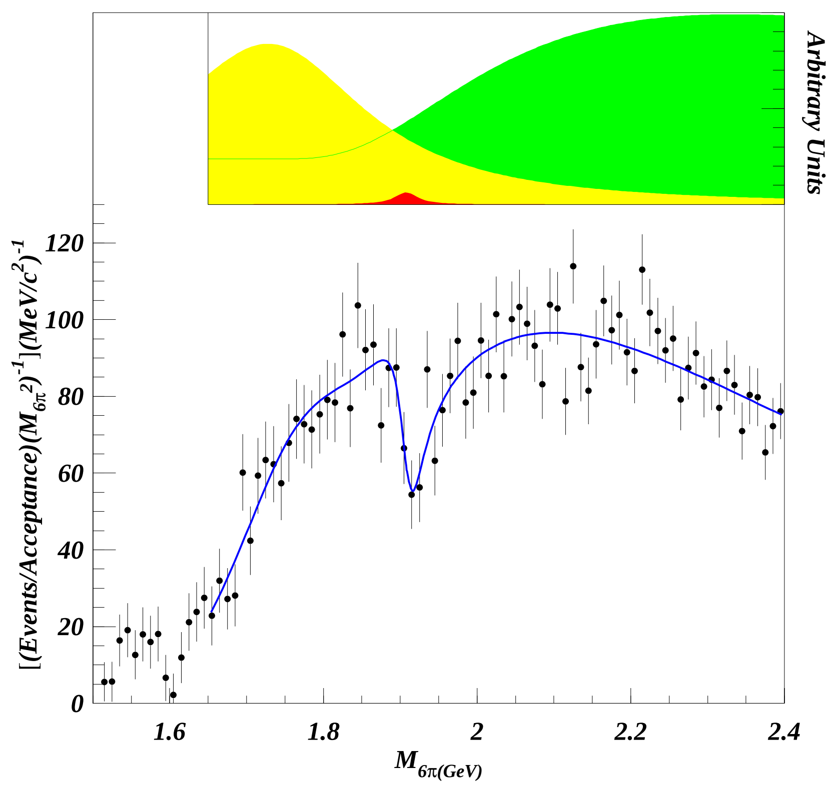
MORE THRESHOLD EFFECTS

J. Rosner, PR D 74, 076006 (2006)

A number of recently-observed effects appear correlated with S-wave thresholds:

- Dip in $\sigma(e^+e^- \to \mathrm{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ near $\sqrt{s} = 4.26$ GeV (lower left)
- Cusp in the $M(\pi^0\pi^0)$ spectrum of $K^\pm \to \pi^\pm\pi^0\pi^0$ at $\pi^+\pi^-$ threshold
- Sharp discontinuities in Dalitz plots for three-body charmed particle decays
- Dip in spectrum of photoproduced $3\pi^+3\pi^-$ at $\bar{p}p$ threshold (lower right)



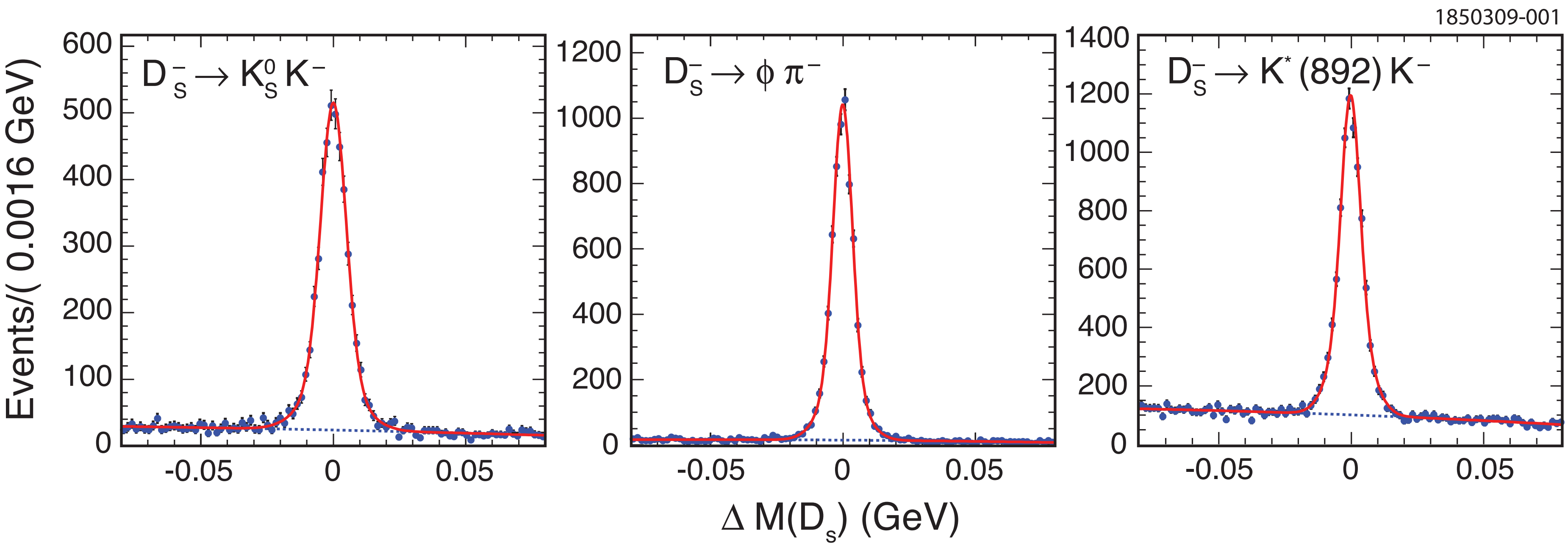


INCLUSIVE D_s DECAYS

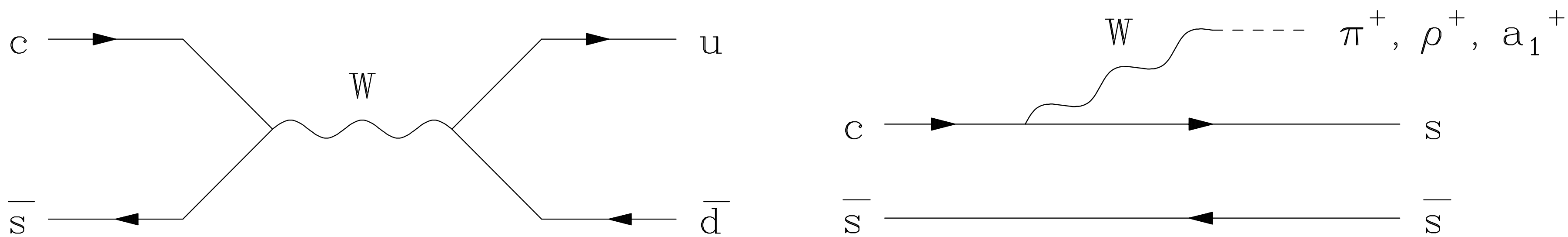
S. Dobbs *et al.* (CLEO Collaboration), Phys. Rev. D **79**, 112008 (2009)

$e^+e^- \to D_s^+ D_s^{*-}$ or $D_s^{*+} D_s^-$; use reconstructed D_s^- as tag of D_s^+

Purity of tag: sum (red) of double-Gaussian signal and background (blue)



Want relative contributions of (e.g.) annihilation (left) vs. W^* emission (right)



D_s^+ PARTICLE YIELDS

Particle	$\mathcal{B}[D_s^+ \to X$ (%)]	
X	CLEO	PDG (2008) and isospin[(a)]
π^+	$119.3 \pm 1.2 \pm 0.7$	125.5 ± 1.11
π^-	$43.2 \pm 0.9 \pm 0.3$	46.6 ± 6.8
π^0	$123.4 \pm 3.8 \pm 5.3$	112.5 ± 8.0
K^+	$28.9 \pm 0.6 \pm 0.3$	27.3 ± 1.4
K^-	$18.7 \pm 0.5 \pm 0.2$	18.4 ± 0.7
η	$29.9 \pm 2.2 \pm 1.7$	32.7 ± 2.9
η'	$11.7 \pm 1.7 \pm 0.7$	18.2 ± 2.1
ϕ	$15.7 \pm 0.8 \pm 0.6$	19.2 ± 2.4
ω	$6.1 \pm 1.4 \pm 0.3$	0.8 ± 0.1

[(a)] M. Gronau + JLR, PR D **79**, 074022 (2009)

Large $\mathcal{B}(D_s^+ \to \omega X)$ motivated search for additional modes

Expect annihilation helicity-suppressed; G-parity forbids $D_s \to (\pi^+\omega, (3\pi^+)\omega)$

Helicity-suppression not apparent in CLEO's result [PRL **100**, 181802 (2008)]:
$\mathcal{B}(D_s \to p\bar{n}) = (1.30 \pm 0.36^{+0.12}_{-0.16}) \times 10^{-3}$ (reasonable form factor)

Difficult to get inclusive ω from $D_s^+ \to W^{*+} s\bar{s}$ (OZI suppression)

EXCLUSIVE D_s DECAYS

J. Y. Ge *et al.* (CLEO Collaboration), Phys. Rev. D **80**, 051102(R) (2009)

Use same sample of 18586 ± 163 tagged events as in inclusive analysis

Mode X	Signal events	$\mathcal{B}(D^s \to X)$ (%)
$\pi^+\omega$	6.0 ± 2.4	$0.21 \pm 0.09 \pm 0.01$
$\pi^+\pi^0\omega$	34.0 ± 7.9	$2.78 \pm 0.65 \pm 0.25$
$\pi^+\pi^+\pi^-\omega$	29.2 ± 8.2	$1.58 \pm 0.45 \pm 0.09$
$\pi^+\eta\ \omega$	4.5 ± 2.9	$0.85 \pm 0.54 \pm 0.06$
Sum		5.4 ± 0.1

Also placed upper limits on modes related to above by (one) $\pi^+ \to K^+$

Accounted for majority of inclusive ω branching fraction $(6.1 \pm 1.4)\%$ but source of two largest modes seems puzzling

If $s\bar{s} \to \omega$ (OZI violation) permitted, might expect to see $D_s^+ \to \omega \ell^+ \nu_\ell$

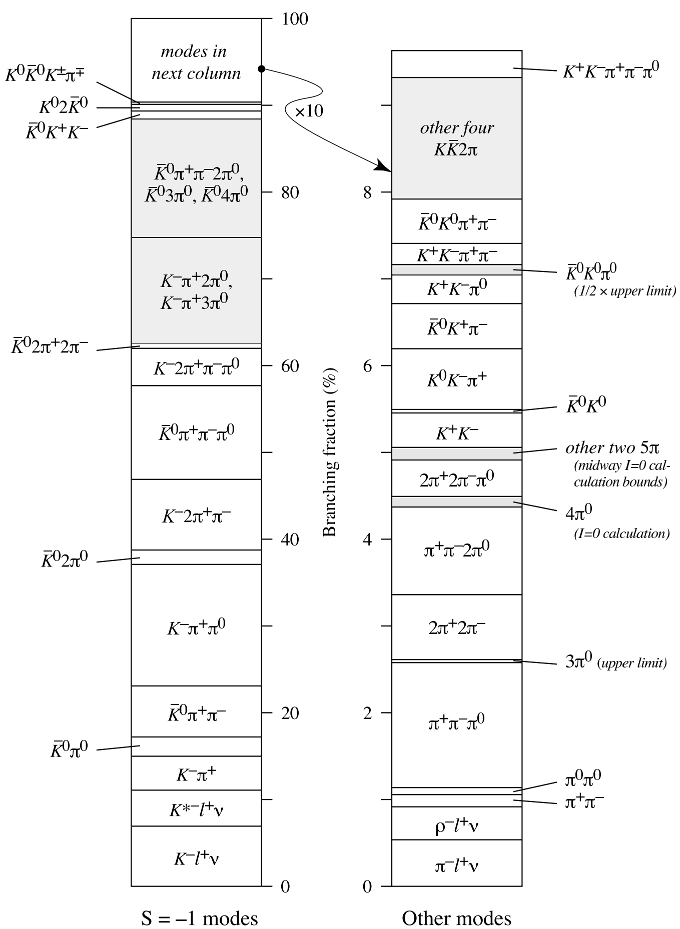
Account for $\simeq 100\%$ of D_s decays in measured exclusive channels

WHAT ABOUT D^0, D^+?

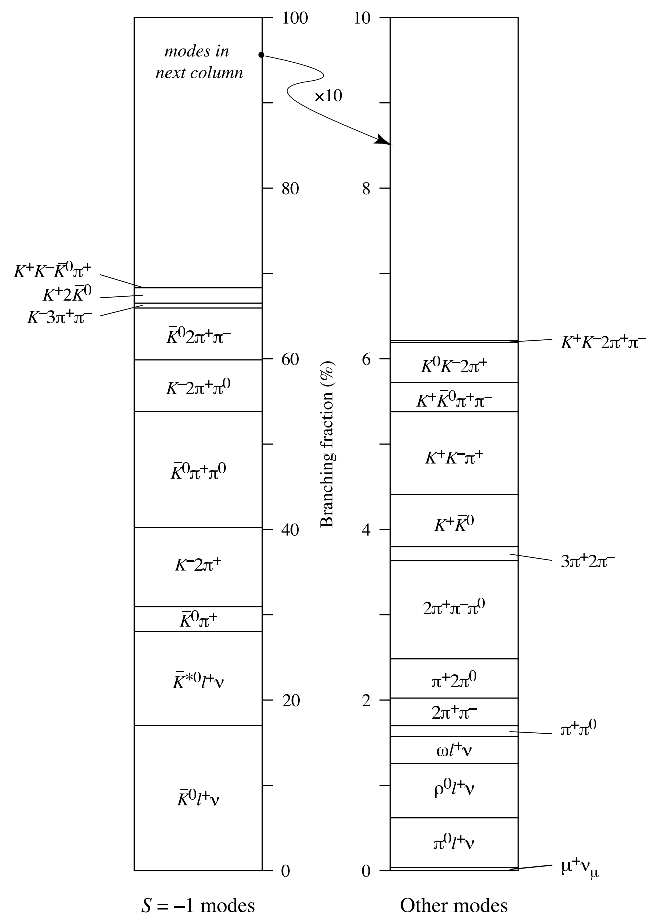
PDG 2008 listings augmented with isospin account well for D_s^+ decays.

Charles Wohl, PDG: isospin estimates ($\neq$ Gronau + JLR) of missing modes

D^0 decays



D^+ decays



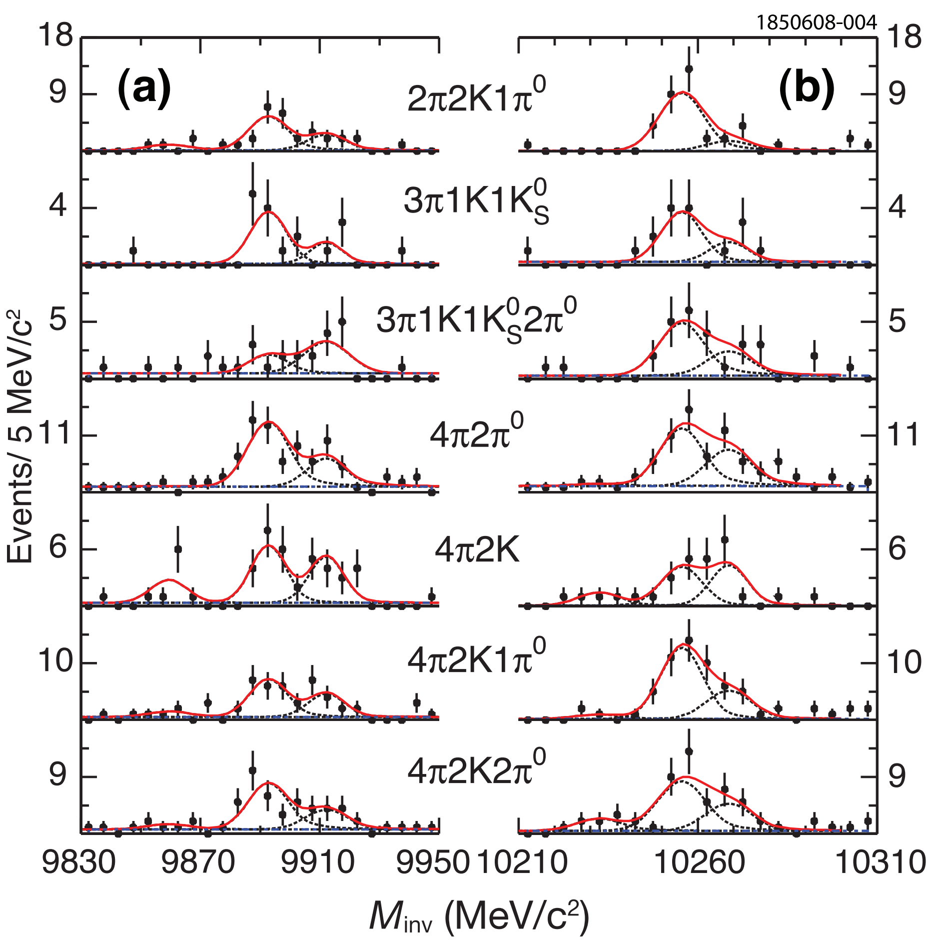
Missing about 1/4 of D^+ decays; probably include those with more than one π^0

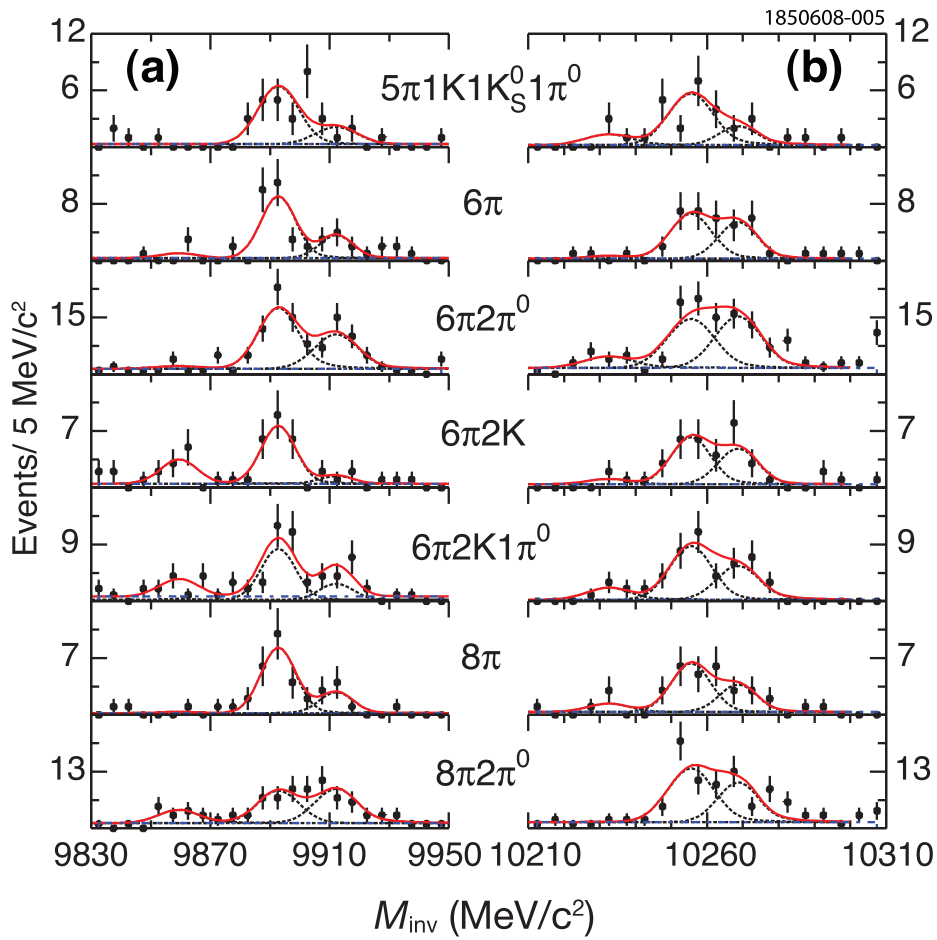
EXCLUSIVE χ_b, χ_b' DECAYS

D. M. Asner *et al.* [CLEO Collaboration], Phys. Rev. D 79, 072007 (2009).

Identified 14 modes with $> 4\sigma$ signals in at least one χ_{bJ} or χ_{bJ}' decay

$\Upsilon(2S) \to \gamma\chi_b$ $\Upsilon(3S) \to \gamma\chi_b'$ $\Upsilon(2S) \to \gamma\chi_b$ $\Upsilon(3S) \to \gamma\chi_b'$



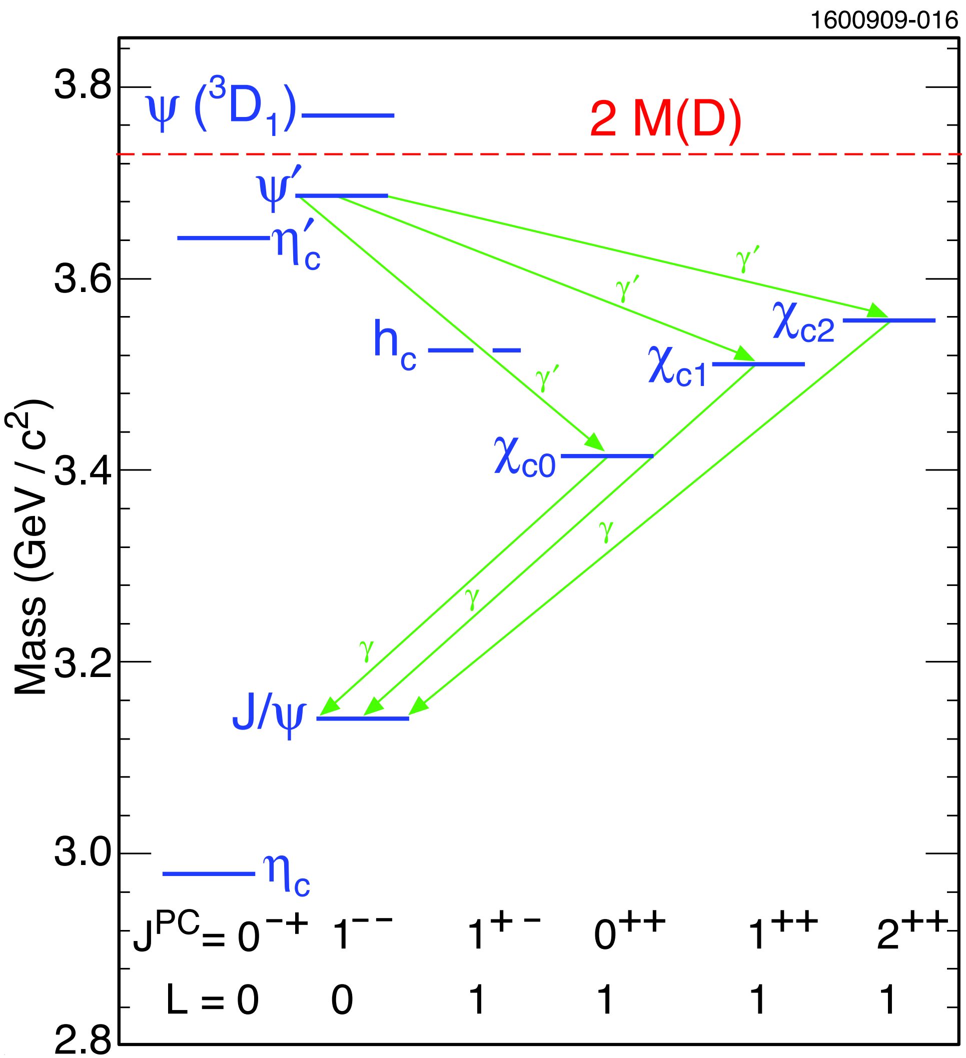


What do Monte Carlo fragmentation programs (PYTHIA, ...) predict?

HIGHER MULTIPOLES IN CHARMONIUM RADIATIVE TRANSITIONS

M. Artuso *et al.*, arXiv:0910.0046 $\Rightarrow$ PRD (in proof)

Analysis initiated by R. Galik ז"ל ; thesis of James Ledoux (Cornell)



Transitions $\psi' \to \gamma\chi_{cJ} \to \gamma\gamma J/\psi$ dominantly electric dipole (E1)

Higher multipoles allowed:
M2 for $J_\chi = 1$; M2 and E3 for $J_\chi = 2$;
No E3 for $S \leftrightarrow P$ single-quark trans.

Angular distributions of photons are sensitive to higher multipoles

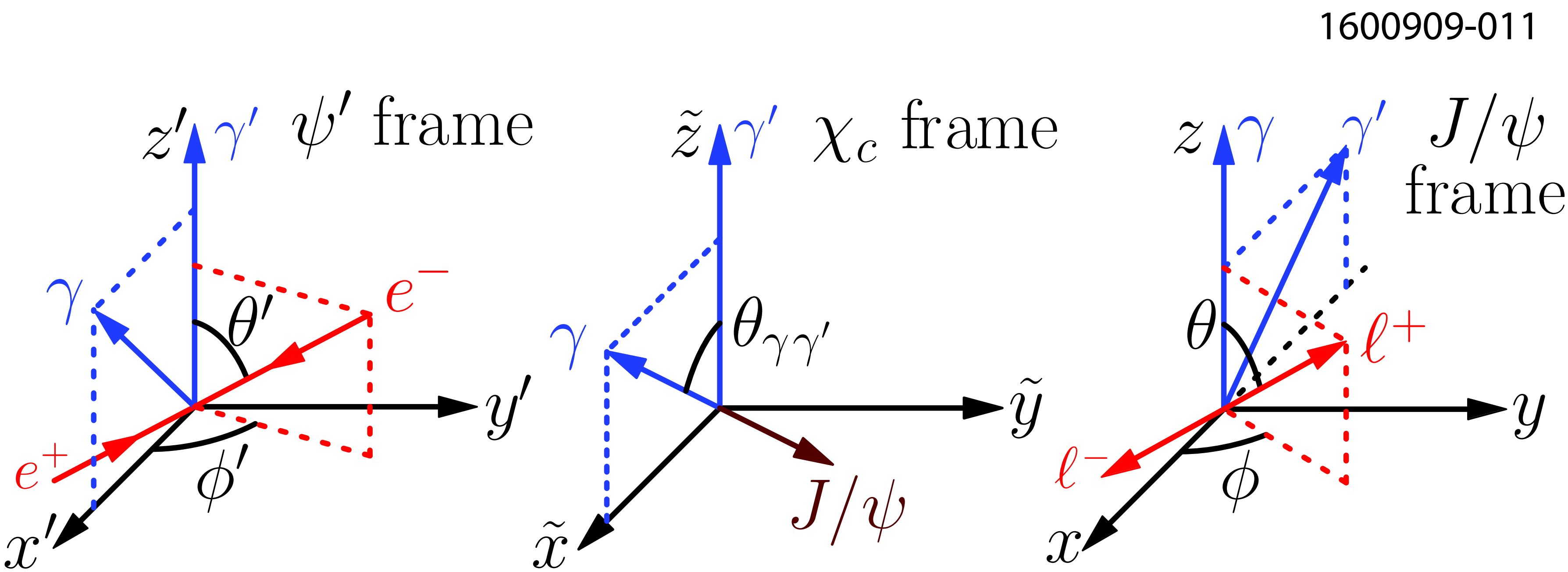
M2 transition measures charmed quark's total magnetic moment

Provides a check of measurements in M1 transitions such as $J/\psi \to \gamma\eta_c$

Prediction of M2 admixture: G. Karl, S. Meshkov, JLR, PRL **45**, 215 (1980)

ANGLE DEFINITIONS

Reaction $e^+e^- \to \psi' \to \gamma'\chi_{cJ} \to \gamma'\gamma J/\psi \to \gamma'\gamma\ell^+\ell^-$ ($\ell = e$ or μ)



Primed angles: initial lepton pair orientation relative to γ' in $\psi' \to \gamma'\chi_{cJ}$

Unprimed angles: final lepton pair orientation relative to γ in $\chi_{cJ} \to \gamma J/\psi$

Angle $\theta_{\gamma\gamma'}$ between γ and γ' in χ_{cJ} rest frame

Angular dist. $W(\cos\theta', \phi', \cos\theta_{\gamma\gamma'}, \cos\theta, \phi)$ depends on helicity amps. B_ν or A_ν:

$\psi'(\lambda') \to \gamma'(\mu') + \chi(\nu')$ (helicity amps. B_ν)

$\chi(\nu) \to \gamma(\mu) + J/\psi(\lambda)$ (helicity amps. A_ν)

HELICITY AMPLITUDES AND MULTIPOLES

Parity relates amplitudes for $\nu, \nu' < 0$ to ones with $\nu, \nu' > 0$

Transform between normalized helicity amps. A (or B) and multipole amps. $a^{J_\chi}_{J_\gamma}$:

$$\begin{pmatrix} A_0^{J=1} \\ A_1^{J=1} \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} \\ \sqrt{\frac{1}{2}} & -\sqrt{\frac{1}{2}} \end{pmatrix} \begin{pmatrix} a_1^{J=1} \\ a_2^{J=1} \end{pmatrix} ,$$

$$\begin{pmatrix} A_0^{J=2} \\ A_1^{J=2} \\ A_2^{J=2} \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{1}{10}} & \sqrt{\frac{1}{2}} & \sqrt{\frac{2}{5}} \\ \sqrt{\frac{3}{10}} & \sqrt{\frac{1}{6}} & -\sqrt{\frac{8}{15}} \\ \sqrt{\frac{3}{5}} & -\sqrt{\frac{1}{3}} & \sqrt{\frac{1}{15}} \end{pmatrix} \begin{pmatrix} a_1^{J=2} \\ a_2^{J=2} \\ a_3^{J=2} \end{pmatrix} .$$

M2 amplitudes related to anomalous moment κ_c of charm quark (potl. indep.!):

$$a_2^{J=1} \equiv \frac{M2}{\sqrt{E1^2 + M2^2}} = -\frac{E_\gamma}{4m_c}(1+\kappa_c)$$

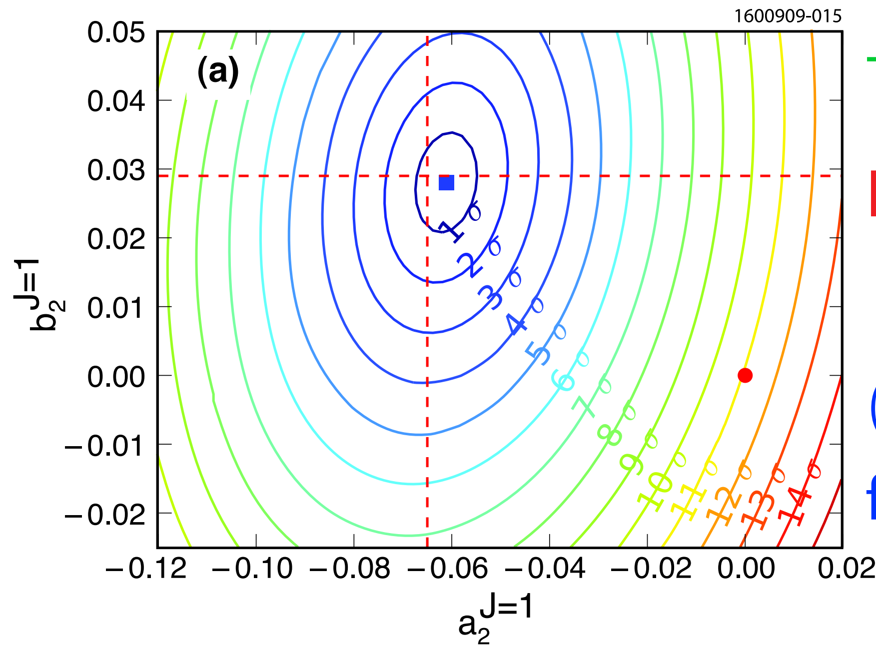
$$a_2^{J=2} \equiv \frac{M2}{\sqrt{E1^2 + M2^2 + E3^2}} = -\frac{3}{\sqrt{5}}\frac{E_\gamma}{4m_c}(1+\kappa_c) \; ;$$

similarly for b amplitudes with sign change, $E_\gamma \to E_{\gamma'}$. These follow from

$$H_I = -\frac{e_c}{2m_c}(\vec{A}^* \cdot \vec{p} + \vec{p} \cdot \vec{A}^*) - \mu \vec{\sigma} \cdot \vec{H}^* + (\mathrm{spin-orbit\ term})$$

$e_c \equiv \frac{2}{3}|e|$; $\mu \equiv (e_c/2m_c)(1+\kappa_c)$; $\vec{A}^*$ and $\vec{H}^* \equiv \nabla \times \vec{A}^*$ refer to emitted photon

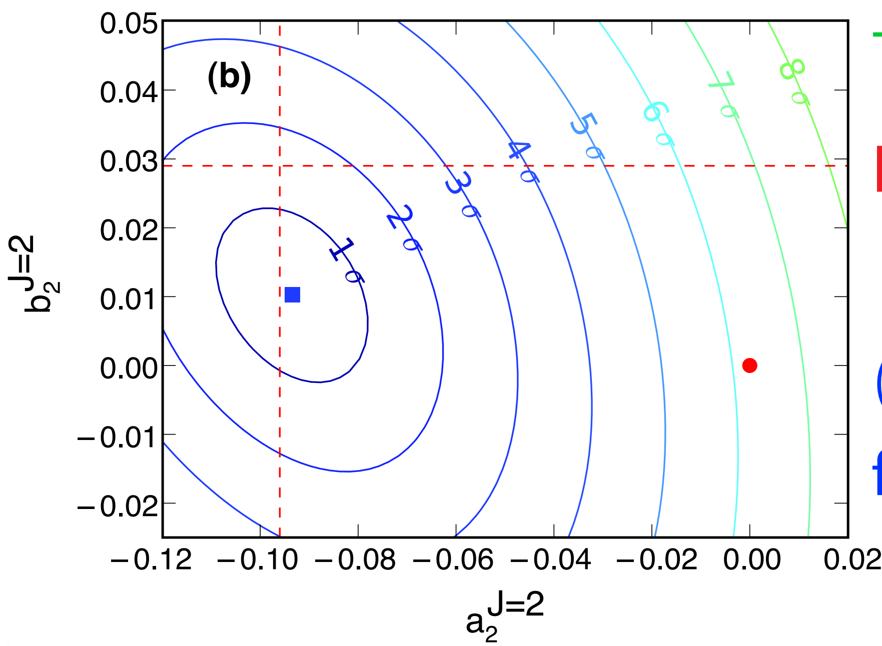
$J_\chi = 1,\ 2$ LIKELIHOODS



Two-parameter fit, $J_\chi = 1$:

Prediction for $\kappa_c = 0$, $m_c = 1.5$ GeV is $(a_2, b_2) = (-0.065, 0.029)$

$(a_2, b_2) = (0, 0)$ ($\bullet$) is 11.1σ from maximum-likelihood solution ($\square$)

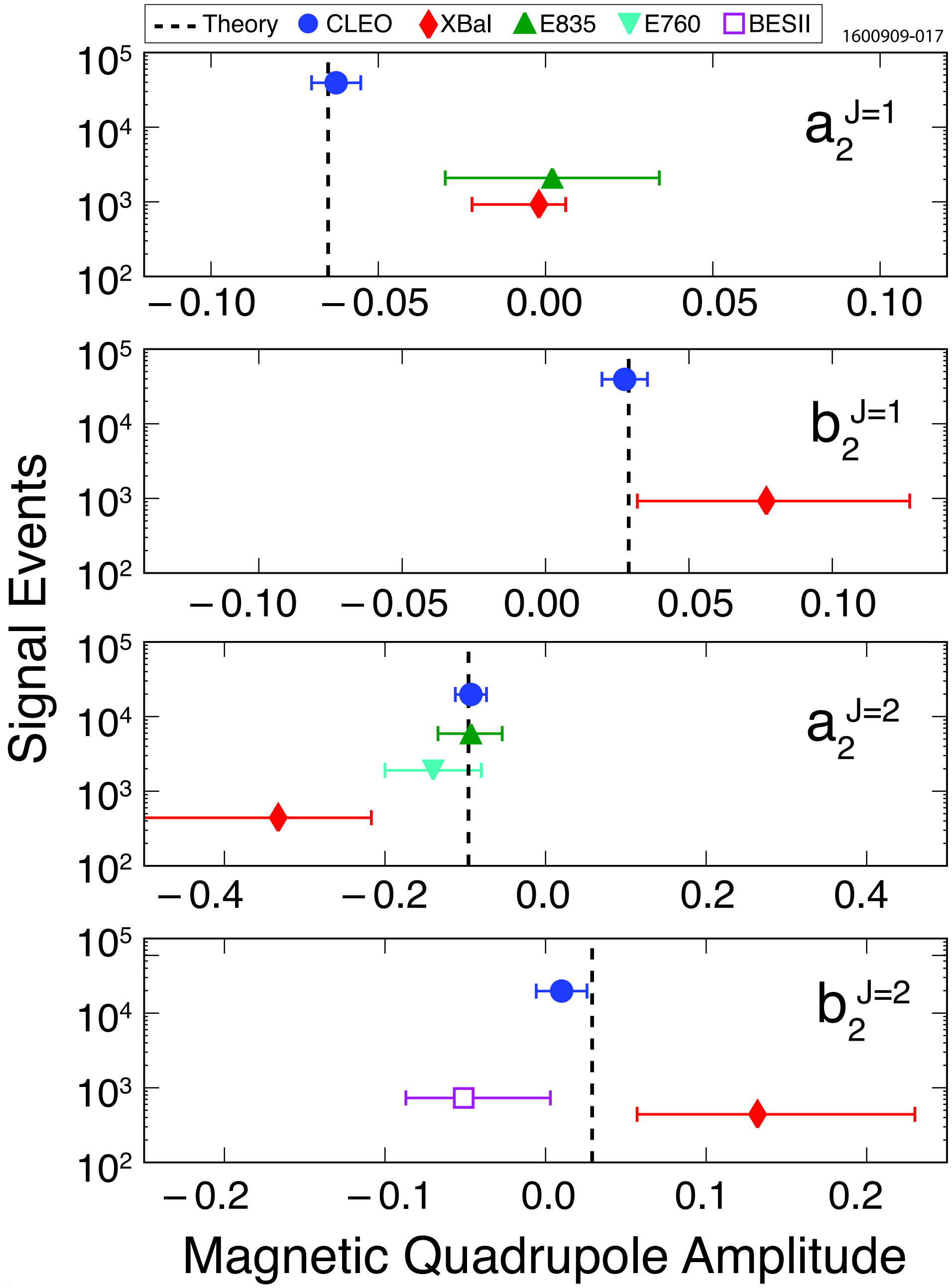


Two-parameter fit, $J_\chi = 2$:

Prediction for $\kappa_c = 0$, $m_c = 1.5$ GeV is $(a_2, b_2) = (-0.096, 0.029)$

$(a_2, b_2) = (0, 0)$ ($\bullet$) is 6.2σ from maximum-likelihood solution ($\square$)

COMPARISON WITH PREVIOUS RESULTS



CLEO-c: circle (two-parameter fit for J_χ=2); Xtal Ball: diamonds; E760: ∇; E835: Δ; BES-II: square; Th. (m_c=1.5 GeV, $\kappa_c = 0$): dashes

First significant evidence for $a_2^{J=1} \neq 0$; $\surd$ prediction

Multipoles $b_2^{J=1}$ and $a_2^{J=2}$ also significantly non-zero and in accord with prediction

Multipole $b_2^{J=2}$ not significant; error reduced w.r.t. previous

No significant evidence for E3 transitions

CONCLUSIONS

Great progress on beauty baryons at Fermilab; masses make sense

Charm/bottom spectroscopy continues to advance: h_c decays; η_b confirmation; B_c; higher multipoles in radiative decays

Inclusive decays of D_s turned up surprising large ω production rate; hard to understand conventionally

Chris and I wondered about exclusive η_c and charm decays [PR D **16**, 1497 (1977); **17**, 239 (1978)]. CLEO has made a good start on η_c; D^0 and D_s modes largely accounted for but 25% of D^+ modes are missing, and several $\times 10^3$ $\chi_{bJ}^{(\prime)}$ modes are likely

See M2 amplitudes for $\chi_{c1} \to \gamma J/\psi$, $\chi_{c2} \to \gamma J/\psi$, and $\psi' \to \gamma' \chi_{c1}$; exclude pure E1 by more than $(11, 6)\sigma$ for $J_\chi = (1, 2)$

Strengths of these amplitudes agree with predictions to $\mathcal{O}(E_{\gamma^{(\prime)}}/m_c)$ with $m_c = 1.5$ GeV and $\kappa_c = 0$

Still learning about (c,b) hadrons after (35,32) years!

HIGHEST b?

Hank Thacker and Chris Quigg on top of Fuji, August, 1978. The Japanese character is pronounce "bi" and stands for beauty.

Thank you, Chris, for showing us the charm and beauty of physics.